

Jet quenching and elliptic flow at RHIC and LHC within a pQCD-based partonic transport model

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Abstract. Fully dynamic simulations of heavy ion collisions at RHIC and at LHC energies within the perturbative QCD-based partonic transport model BAMPS (Boltzmann Approach to Multi-Parton Scatterings) are presented, focusing on the simultaneous investigation of jet quenching and elliptic flow. The model features inelastic $2 \leftrightarrow 3$ processes based on the Gunion-Bertsch matrix element and has recently been extended to include light quark degrees of freedom, allowing for direct comparison to hadronic data on the nuclear modification factor via a fragmentation scheme for high- p_T partons. The nuclear modification factor of neutral pions in central Au + Au collisions at RHIC energy is compared to experimental data. Furthermore first results on the nuclear modification factor and the integrated elliptic flow of charged hadrons in Pb + Pb collisions at LHC are presented and compared to recent ALICE data. These investigations are complemented by a study on the suppression of D -mesons at LHC based on elastic interactions with the medium.

1. Introduction

The suppression of high- p_T spectra with respect to a scaled p + p reference, quantified in terms of the nuclear modification factor R_{AA} , and the strong collectivity of the medium, quantified in terms of the Fourier coefficient v_2 , the elliptic flow, have been established by experiments at the *Relativistic Heavy Ion Collider* (RHIC). First results from the recently commissioned *Large Hadron Collider* (LHC) have confirmed these findings at an order of magnitude higher collision energy, showing remarkable quantitative similarities beyond a good qualitative agreement. The suppression of particles with high transverse momentum is commonly attributed to an energy loss on the partonic level during the quark-gluon plasma (QGP) stage of the evolution of the medium. Comparison of v_2 measurements to hydrodynamic simulations have established that the elliptic flow builds up early and is thus also governed by the evolution of the QGP medium. It is notoriously difficult to combine both aspects of the QPG evolution—the suppression of rare, high- p_T probes and the collective behavior of the bulk particles—into a common model. The work presented in this article explores the capabilities of microscopic partonic transport models in this respect.

2. The transport model BAMPS

The microscopic transport model BAMPS (*Boltzmann Approach to Multi-Parton Scatterings*) [1] is applied to simulate the time evolution of the hot partonic medium that is created in heavy ion collisions at RHIC and LHC. It is based on matrix elements in leading order perturbative QCD (pQCD) and consistently features inelastic $2 \leftrightarrow 3$ interactions. Rapid thermalization of the simulated partonic medium on the order of $1 \text{ fm } c^{-1}$ has been found for Au + Au collisions at RHIC energies [1] and can be confirmed also for Pb + Pb collisions at LHC energies.

Originally limited to a purely gluonic medium ($N_f = 0$) the model has been extended to include light quarks ($N_f = 3$). These are considered to be massless Boltzmann particles as are the gluons. Binary interactions involving light quarks and gluons are computed from leading order pQCD cross sections in small angle approximation. Radiative and annihilation processes, $gg \leftrightarrow ggg$, are based on the Gunion-Bertsch matrix element [2]

$$|\mathcal{M}_{gg \rightarrow ggg}|^2 = \left(\frac{72\pi^2 \alpha_s^2 s^2}{(\mathbf{q}_\perp^2 + m_D^2)^2} \right) \left(\frac{48\pi \alpha_s \mathbf{q}_\perp^2}{\mathbf{k}_\perp^2 [(\mathbf{k}_\perp - \mathbf{q}_\perp)^2 + m_D^2]} \right). \quad (1)$$

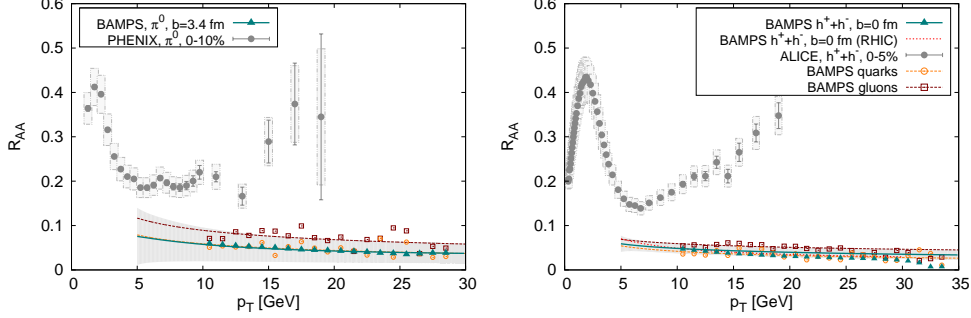
$2 \leftrightarrow 3$ processes involving light quarks are also computed from (1) based on a factorization of the Gunion-Bertsch matrix element into a collisional part and a radiation probability $|\mathcal{M}_{\text{GB}}|^2 = |\mathcal{M}_{\text{coll}}|^2 P^g$. Applying the small angle approximation to $|\mathcal{M}_{\text{coll}}|^2$, the computation of $2 \leftrightarrow 3$ processes involving light quarks is reduced to a scaling of (1) by color and symmetry factors.

The cross sections and matrix elements are screened by a Debye mass $m_D^2 = d_G \pi \alpha_s \int \frac{d^3 p}{(2\pi)^3} \frac{1}{p} (N_c f_g + N_f f_q)$ that is dynamically computed from the current distributions of gluons and quarks. The Landau-Pomeranchuk-Migdal (LPM) effect is modeled via the introduction of a cutoff $\Theta(\lambda - \tau)$ into (1) that effectively discards coherent contributions from multiple induced gluon radiation. This is done by a comparison of the mean free path λ to the formation time of the radiated gluon τ . More details on the modeling of the LPM effect and on the consequences arising from this implementation can be found in [3].

3. Nuclear modification factor and elliptic flow for gluons and light quarks

As established in [4, 5, 6] the matter in BAMPS simulations of Au + Au collisions at RHIC energies exhibits a strong degree of collectivity with an integrated v_2 that is in good agreement with experimental results over a large centrality range for a fixed strong coupling of $\alpha_s = 0.3$ and a freeze-out energy density $\varepsilon_c = 0.6 \text{ GeV fm}^{-3}$. These parameters are used for all calculations that are presented in this section.

Using this setup and mini-jet initial conditions with $p_0 = 1.4 \text{ GeV}$, figure 1a shows the nuclear modification factor R_{AA} obtained from BAMPS simulations of central, 0%–10%, Au + Au collisions at 200 A GeV. The results are both shown on the partonic level for gluons and light quarks and on the hadronic level for neutral pions based on AKK fragmentation functions [9]. The suppression of high- p_T particles in simulations with BAMPS is distinctly stronger than the experimentally observed suppression. This is due to a) a strong energy loss that is caused by a complex interplay of the Gunion-Bertsch matrix element and the effective implementation of the LPM effect [3], b) a conversion of quark into gluon jets in $2 \rightarrow 3$ interactions and c) a small



(a) Nuclear modification factor R_{AA} for neutral pions from BAMPS simulations of Au + Au at 200 A GeV compared to PHENIX results [7] at 0%–10% centrality. R_{AA} of gluons and quarks is shown for comparison. Lines indicate R_{AA} computed from fits to the parton spectra, while symbols indicate R_{AA} computed directly from the parton spectra as obtained from BAMPS.

(b) Nuclear modification factor R_{AA} of charged hadrons, gluons and quarks from BAMPS simulations of Pb + Pb at $b = 0$ fm compared to results from ALICE for 0%–5% central Pb + Pb collisions [8]. Lines and symbols as in figure 1a. For comparison the R_{AA} of charged hadrons from simulations of Au + Au at 200 A GeV and $b = 0$ fm is also shown.

Figure 1. Nuclear modification factor at RHIC and LHC.

difference in the energy loss of gluons and quarks caused by the iterative computation of interaction rates required by the inclusion of the LPM cutoff into (1).

Going to the LHC energy of $\sqrt{s_{NN}} = 2.76$ TeV and using PYTHIA initial conditions [10], figure 1b shows the nuclear modification factor of charged hadrons for central Pb + Pb collisions. The results are not significantly different from those at RHIC energy and again the suppression of high- p_T particles is overestimated compared to the experimental data. Also the upward trend towards large p_T present in the ALICE data is not reproduced.

The simulated differential v_2 of central and semi-central Pb + Pb collisions at 2.76 A TeV shows no significant deviation from the Au + Au results at 200 A GeV in the low to intermediate p_T region which is in agreement with experimental findings [8]. Following from an increase in the mean transverse momenta, the integrated v_2 however is larger. Figure 2a shows the integrated v_2 for Pb + Pb at LHC as a function of centrality compared to experimental data from ALICE [8]. Up to roughly 40% centrality the agreement is very good, going to more peripheral collisions the simulated v_2 exhibits a drop that is distinctly more pronounced than in the experimental data. The cause of this rapid drop is currently under systematic investigation, comparing for example different initial conditions and freeze-out prescriptions.

4. Heavy quarks

The BAMPS framework is also extensively applied to the investigation of heavy quark phenomena [10, 11, 12]. Figure 2b compares the R_{AA} of D -mesons obtained from BAMPS to preliminary ALICE data [13]. Heavy quark elastic interactions with the gluonic medium ($N_f = 0$) are implemented with running coupling and a Debye screening motivated from HTL calculations [12]. To account for radiative contributions the cross section is multiplied by a factor $K = 4$ which gives a very good agreement

with experimental data for R_{AA} and v_2 of heavy flavor electrons at RHIC [12]. It will be checked in a forthcoming study whether the implementation of radiative heavy quark processes has indeed the same effect as scaling the elastic cross section with a constant K factor.

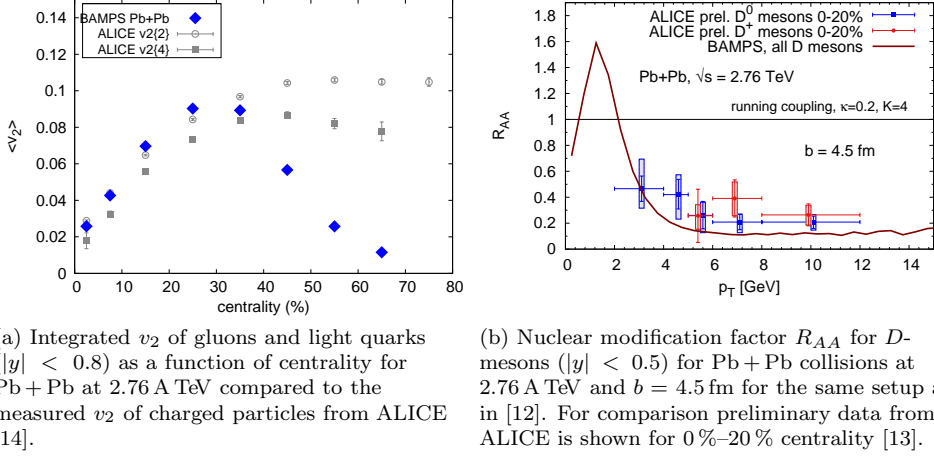


Figure 2. Integrated v_2 and D -meson R_{AA} at LHC.

5. Summary

The transport model BAMPS allows for the simultaneous investigation of both the suppression of high- p_T particles and the collectivity of bulk particles consistently within a common setup that handles gluons as well as light and heavy quarks. Employing the same parameters that give a good description of the integrated elliptic flow at RHIC energies, the suppression of high- p_T particles from gluons and light quarks is too strong. The same holds for simulations of Pb+Pb collisions at LHC, where no significant differences in the suppression pattern and the differential elliptic flow are observed compared to RHIC simulations. The integrated elliptic flow at LHC is well described up to 40 % centrality, for more peripheral collisions the simulated v_2 drops too fast. Fixing the interaction of heavy quarks via elastic interactions with the medium to the suppression of heavy flavor electrons at RHIC by means of a K factor, the elliptic flow of heavy flavor electrons at RHIC as well as the suppression of D -mesons at LHC can be reproduced.

Future studies will investigate the important effect of a running coupling on the R_{AA} of gluons and light quarks and also systematically explore the implementation of the LPM effect. These modifications are qualitatively expected to bring the results for the nuclear modification factors into better agreement with experimental data. The consequences of radiative processes on the dynamics of heavy quarks will also be investigated in an upcoming study.

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